Stationary High Confinement Plasmas with Large Bootstrap Current Fraction in JT-60U

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Abstract. This paper reports results on the progress in stationary discharges with a large bootstrap current fraction in JT-60U towards steady-state tokamak operation. In weak shear plasma regime, high-β_p ELMy H-mode discharges have been optimized under nearly full non-inductive current drive by the large bootstrap current fraction (f_{BS}~50%) and the beam driven current fraction (f_{BD}>40%), which was sustained for ~2.3s with stationary condition. The high confinement enhancement factor H_{89}~2.3 (HH_{98y2}~1.0) was also sustained under the condition of T_e~T_i. In reversed shear plasma regime, the large bootstrap current fraction (f_{BS}~75%) has been sustained for 7.4 s under nearly full non-inductive current drive condition. The high confinement enhancement factor H_{89}~3.0 (HH_{98y2}~1.7) was also sustained, and the profiles of current and pressure approached the stationary condition. The large bootstrap current and the off-axis beam driven current sustained this reversed q-profile. This duration was limited only by the duration of the neutral beam injection.

1. Introduction

For steady-state operation of tokamak, full non-inductive current drive condition is required to sustain the plasma current due to the limited inductive flux [1]. The key factor to reduce a circulating power for non-inductive current drivers is the use of bootstrap currents driven by the high β plasma itself. The scenario for the ITER steady-state operation with Q>5 have been proposed [2], in which high β_N with the large bootstrap current fraction of ~50%. Further large bootstrap current fraction (~75%) is required for the concept of steady-state fusion tokamak reactor (SSTR) [1]. The 2004 campaign for advanced tokamak experiments on JT-60U focused on the stationary high confinement plasmas with large bootstrap current fraction towards the steady-state operations for ITER and SSTR.

JT-60U has been optimizing the scenario for the steady-state operation by using two advanced tokamak operational modes [3], that is the high β_p H-mode plasma so-called weak shear plasma and the reversed shear plasma. The magnetic shear configurations of these plasmas are naturally formed with a large bootstrap current fraction. This is the reason why these operational modes in JT-60U are the candidate of the steady-state operation scenario for ITER and SSTR. The purpose of the advanced tokamak experiments on JT-60U is to search for a suitable magnetic configuration to attain the steady-state operation of tokamak, and is to clarify the issues. One of the key issues in weak shear plasma regime to attain the stationary discharge towards steady-state operation is to avoid the destabilization of neoclassical tearing modes (NTMs). We have attempted two approaches. One is avoidance of destabilization by optimization of current profile and another is stabilization by electron cyclotron current drive. The latter approach is discussed in Ref. 4 and 5. As for the reversed shear plasma regime, on the other hand, the relatively lower beta limit is one of the issues towards steady-state operation [6, 7]. We have attempted two approaches from the previous experiments. One is the control of total pressure profile by large H-mode pedestal using high triangularity configuration. Another is the control of local pressure profile by the control of toroidal rotation. In this paper, the developments of stationary discharges with a large fraction (f_{BS}) of bootstrap current to the plasma current are reported in two regimes of weak magnetic shear and reversed magnetic shear plasmas in JT-60U.

2. Weak Shear Plasma Regime

The high β_p H-mode plasma in JT-60U is characterized by a monotonic safety factor (q) profile with weak magnetic shear thanks to the bootstrap current based on the internal transport barrier (ITB) formation. Such a weak shear configuration is compatible with the ITER steady-state operation with Q>5. To date, the high β_p H-mode plasmas had been optimized to realize the steady-state operation scenarios for ITER [3, 4]. However, the pulse length of full non-inductive current drive phase was limited up to ~2 s by the pulse length of negative-ion-based neutral beams (N-NB) and/or resistive instabilities such as NTMs. By extending the pulse length of N-NB, this domain of operation is investigated.

Typical waveforms of nearly full non-inductive current drive discharge in weak shear regime are shown in Fig. 1. Plasma parameters are as follows: plasma current I_p=1 MA, toroidal magnetic field B_T=2.4 T, major radius R=3.35 m, minor radius a=0.8 m, elongation κ=1.44, triangularity δ=0.5, safety factor at the 95% flux surface q_{95}=4.4. By injections of N-NB (~3 MW, 6 s) and P-NB (co-tangential: ~4.5 MW, ctr-tangential: ~0.9 MW, perpendicular: ~14 MW) for the non-inductive current drive and heating, β_N~2.4 has been sustained for 5.5 s. Although the fraction (f_{CD}) of the non-inductive current to the plasma current is not 100%, f_{CD}~82-97% with f_{BS}~42% is maintained. However q(0) is just above unity and q=1.5 surface locates 50% of normalized minor radius as shown in Fig. 1(c), then 3/2 mode was observed after β_N>2.5. The confinement enhancement factor over the L-mode scaling (H_{89}) is ~1.8.

It is required for the complete avoidance of the 3/2 mode that the value of q in the whole region is beyond 1.5. In addition, it is preferable that the location of q=2 shifts quite outwards, at which the pressure gradient can be small enough so as the mode to occur, thanks to the large bootstrap current driven at off-axis region. The experimental scenario as follows: (1) The P-NB is injected at q(0) just above 1.5 and the stored energy is carefully raised by feedback control by perpendicular P-NB to avoid the occurrence of 2/1 mode. (2) N-NB is injected for full non-inductive current drive condition when β_N reaches at ~2.5. At this stage, the bootstrap current is fully developed, and then weak shear configuration will be formed. An inductive current component will be replaced with the beam driven current by N-NB. (3) Feedback control of stored energy by P-NB is continued to keep β_N in the constant until the

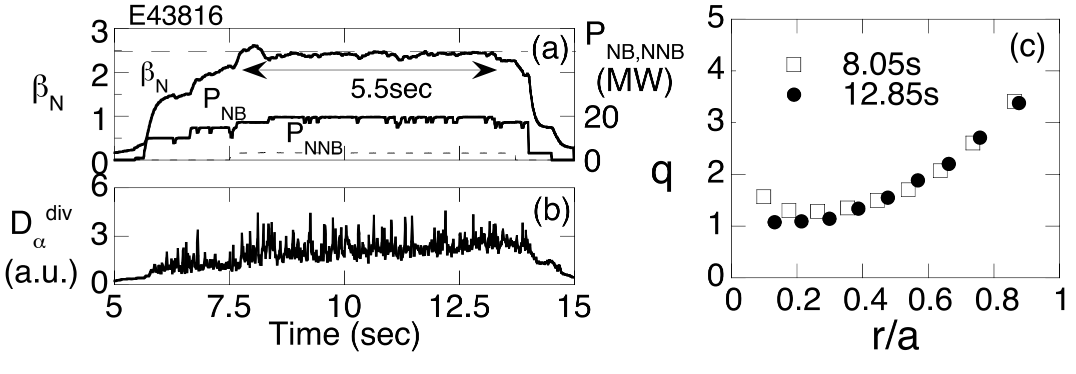

FIG 1. Typical waveforms of nearly full non-inductive current drive discharge in weak shear regime: (a) injected power of P-NB and N-NB, and normalized beta, (b) D_α emission from divertor region. (c) Time evolution of q-profile.

end of NB heating.

Typical waveforms of such scenario are shown in Fig. 2. Plasma parameters are similar to previous one as shown in Fig. 1. The plasma with β_N~2.4 has been sustained for 3.3 s. Loop voltage is kept around zero, which indicates the nearly full non-inductive current drive condition. The analysis of non-inductive current drive indicates that f_{BS} ~50% and f_{BD}>40% were obtained. In this discharge, H_{89}~2.3 and the confinement enhancement factor over the ELMy H-mode scaling HH_{98y2} is ~1.0. The injected power of P-NB decreased after N-NB injection due to feedback control of stored energy. Since N-NB heats electrons mainly due to high beam energy (~355 keV in this discharge). The deposition heating power and the beam driven currents are calculated by the orbit following Monte Carlo (OFMC) code [8], in which the behaviour of 10000-20000 test particles for fast ions generated by NB injectors is traced until they are entirely thermalized or lost from the plasma due to ripple loss, orbit loss, and charge exchange loss. The deposition powers to ions and electrons are nearly equal during N-NB injection. Since the power to ions is ~6 MW and that to electrons is ~5 MW in this discharge, the electron temperature is similar to the ion temperature as shown in Fig. 2(g). The other important feature in this discharge is behaviour of q profile. The shape of q profile at just after NB injection (t=5.6 s) is monotonic and q(0)>1.5. During P-NB heating, the shape of q profile become flatter at t= 7.9 s, namely the formation of weak shear configuration. The q profile in core region becomes slightly reverse due to increase in bootstrap current at off-axis region. During this high performance phase, no 3/2 mode was observed thanks to q_{min}~1.5. The change in the shape of q profile is small during N-NB injection. This indicates that the inductive current before N-NB injection could be replaced with the beam driven current by N-NB. The profiles of ion and electron temperatures and density are almost no change after the fast ions produced by N-NB are thermalized. Duration of this high integrated

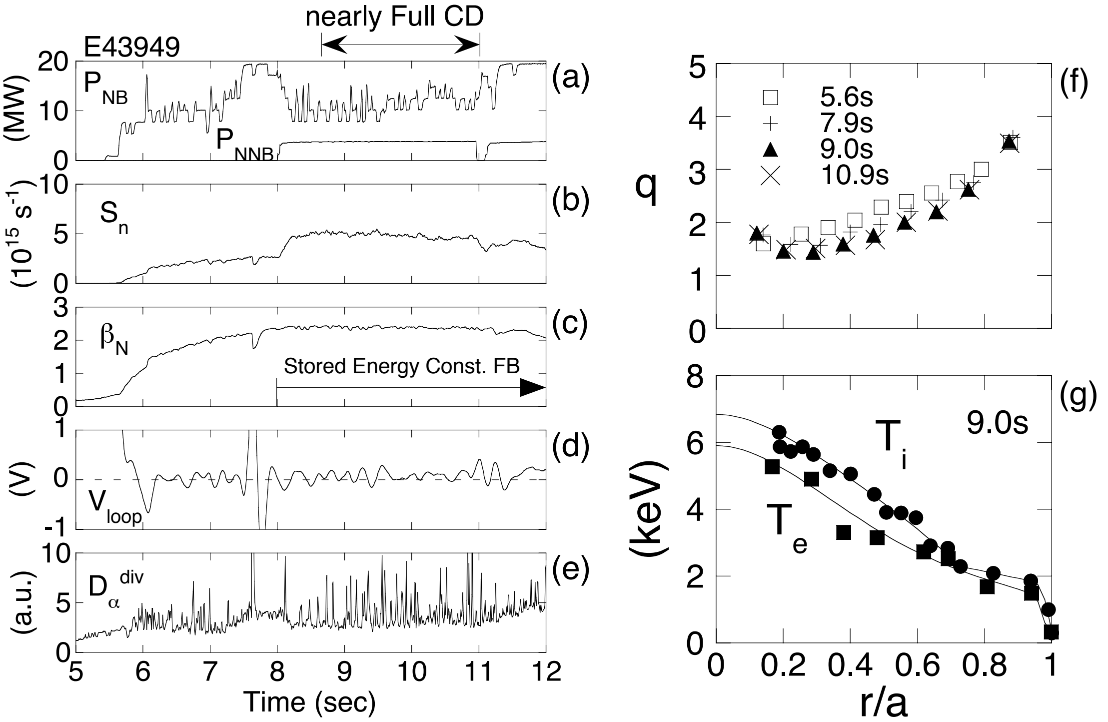

FIG. 2. Typical waveforms of nearly full non-inductive current drive discharge in weak shear regime: (a) injected power of P-NB and N-NB, (b) neutron emission rate, (c) normalized beta, (d) loop voltage, (e) intensity of D_α emission from divertor region. (f) Time evolution of q-profile. (g) profiles of ion and electron temperatures at t=9.0 s.

performance phase determined by loss of internal transport barriers after the breakdown of N-NB at t=11.0 s.

3. Stationary Reversed Shear Plasma with Large Bootstrap Current Fraction

Further large bootstrap current fraction (~75%) is required for the concept of SSTR. In JT-60U, a quasi-steady reversed shear plasma with the large f_{BS}~80% had been sustained for 2.7s under the full non-inductive current drive condition [7]. In order to confirm applicability of the plasma with the large f_{BS} to the steady-state reactor, it is important to demonstrate the longer sustainment of the large f_{BS} plasmas. Since the current and the pressure profiles are strongly coupled in the reversed shear plasma, the main objective of this regime is to investigate whether the reversed shear plasma is stable until the current and the pressure profiles become stationary. Toward this, we have proceeded with the development of the reversed shear plasmas with the ELMy H-mode edge.

3.1 Discharge Optimization

A high q_{95} regime was chosen to enhance β_p and a bootstrap current fraction within the attainable beta limit typically imposed by $\beta_N<2$ in JT-60U reversed shear plasmas without wall stabilization [6]. A high δ configuration was utilized to obtain high β_N. The differences with the previous scenario for the quasi-steady reversed shear plasma are the waveform of plasma current and the setup timing of high δ configuration. In the previous scenario [7], the initial overshooting of plasma current was employed as an experimental technique that was meant to reduce the minimum value of q (q_{min}) rapidly to an expected steady-state value and to form strong ITBs safely below beta limit, and high δ configuration set after ramp-down of plasma current. At this time, no overshooting of plasma current was employed and high δ

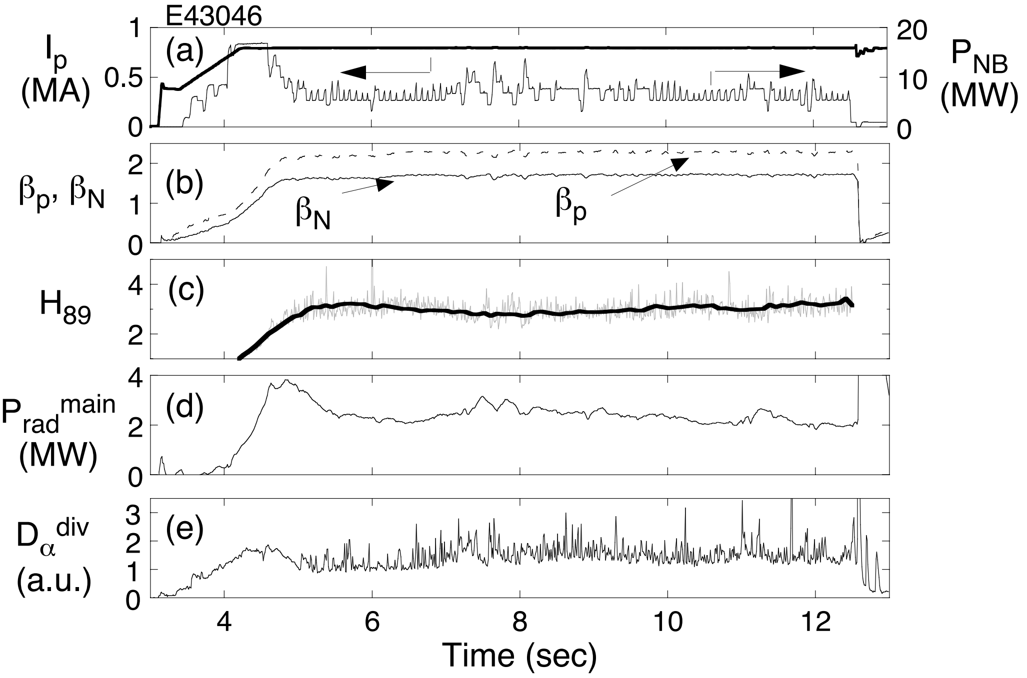

FIG. 3. Typical waveforms of stationary reversed shear plasmas with ELMy H-mode edge: (a) Plasma current and injected power of P-NB, (b) normalized beta (solid curve) and poloidal beta (dotted curve), (c) confinement enhancement factor over the L-mode scaling (H_{89}), (d) radiation power from main plasma region, (e) intensity of D_α emission from divertor region.

configuration was set before the flattop of plasma current. The modification of waveform of plasma current enables us to produce the plasma with a large bootstrap current fraction for longer time under the limited pulse length of NBs. The strong ITB could be safely formed below beta limit thanks to higher pedestal pressure led by high δ configuration.

Typical waveforms of the reversed shear ELMy H-mode discharge are shown in Fig. 3, where I_p=0.8 MA, B_T=3.4 T, q_{95}~8.6, κ=1.6, δ=0.42. The NBs with the different injection directions were used properly. The co-NB power of ~3.2 MW was injected for the current drive, and the ctr-NB power of ~0.9 MW was injected for the MSE measurement. The ITB was formed during I_p ramp, and the ETB was also formed at t=4.5 s. Using the feedback control of the stored energy by the perpendicular NBs, β_N~1.7 (β_p~2.25) was maintained from t~5.1 s until the end of the NB heating (t=12.5s). The high H_{89} of 3.0 was also maintained thanks to both ITB and ETB. The thermal component of the plasma-stored energy was 73-78%, and the enhancement factor of thermal confinement to the scaling for ELMy H-mode (HH_{98y2}) was 1.7-1.9. This duration of ~7.4 s corresponds to16 times the energy confinement time (τ_E~0.46 s). It should be mentioned that no strong impurity accumulation was observed as shown in Fig. 3(d), where the radiation power from main plasma region (P_{rad}^{main}) was almost constant during this high performance phase.

For the long sustainment of the reversed shear ELMy H-mode plasmas, mini-collapse and disruption should be avoided until current and pressure profiles become stationary. The discharges sometimes terminated by a disruption before reaching stationary when the value of q_{min} passed through integer values. The disruption could be avoided by the control of ITB strength through the toroidal rotation control. Figure 4 shows the time evolution of β_N in E43042 and E43046 and the ion temperature at several radii in E43046. The disruption occurred at q_{min} ~4 in E43042, where ~3.2 MW of co-NB and ~0.9 MW of ctr-NB were injected through the discharge. In order to avoid this disruption, the control of ITB strength through toroidal rotation control [9] was utilized for E43046. The ctr-NB for the MSE measurement was switched off from 7-8 s, and then the ITB strength degraded as shown in Fig. 4(b). Although small MHD events occurred during the interruption of ctr-NB, no disruption was observed in E43046.

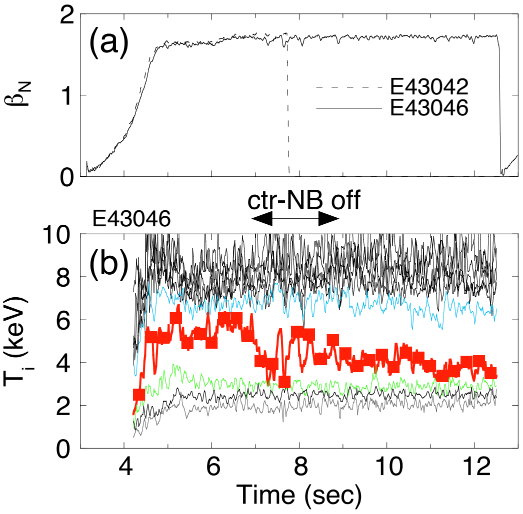

FIG. 4. Control of strength of internal transport barrier by toroidal rotation. (a) Time traces of normalized beta of the discharge with toroidal rotation control (E43046), and that without control (E43042). (b) Time evolution of ion temperatures in each radial location.

3.2 Evolution of current and pressure profiles

Since a hollow current profile tends to become parabolic through the penetration of inductive current, the off-axis non-inductive current having the suitable alignment with q-profile is required for the stationary sustainment. Time evolutions of the q_{min} and its location (ρ_{qmin}) in E43046 are shown in Fig. 5. These values decrease gradually in time towards steady-state condition and they become almost steady after t~10 s. The profiles of q and ion temperature (T_i) approached the stationary condition as shown in Figs. 6(a) and (b). The current hole [10] remained through the discharge at the region r/a<0.2. The strong reversed shear was formed at t=5.1 s, and then the magnetic shear became weaker at the stationary phase. It should be mentioned that the strong reversed shear is required during the ITB formation phase, while that is no necessary for the susutainment of ITB. At the stationary phase, the profile of measured total current density (j_{tot}^{mea}) agreed closely with that of calculated non-inductive current density ($j_{BS}^{cal}+j_{BD}^{cal}$) as shown in Fig. 6(c). In addition the internal loop voltage shown in Fig. 6(d) is small and almost flat, which implies the plasma approached the stationary condition. However more time is required for full relaxation of the internal loop voltage. These indicate the inductive current was small. Actually the Ohmic current estimated from profiles of the loop voltage and neoclassical resistivity is ~8% of total plasma current. Therefore nearly full non-inductive current drive condition is achieved and that is susutained for 7.4 s.

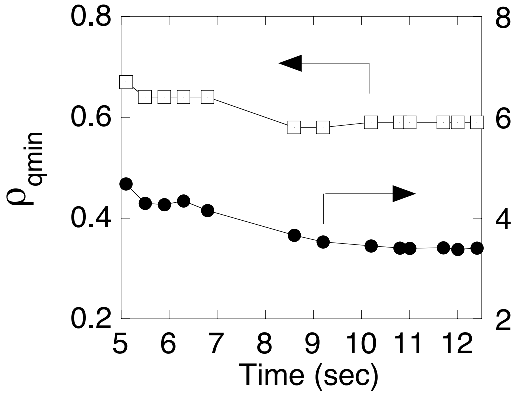

FIG. 5. Time evolutions of the q_{min} and its location (ρ_{qmin}). They became almost steady state after t=10 s.

The fraction of bootstrap current was ~75% and the amount of beam driven current was evaluated to be ~0.16 MA or ~20% of plasma current. The sum of the bootstrap current and the beam driven current is >90% of plasma current for t=5.1-12.5 s, and then the nearly full

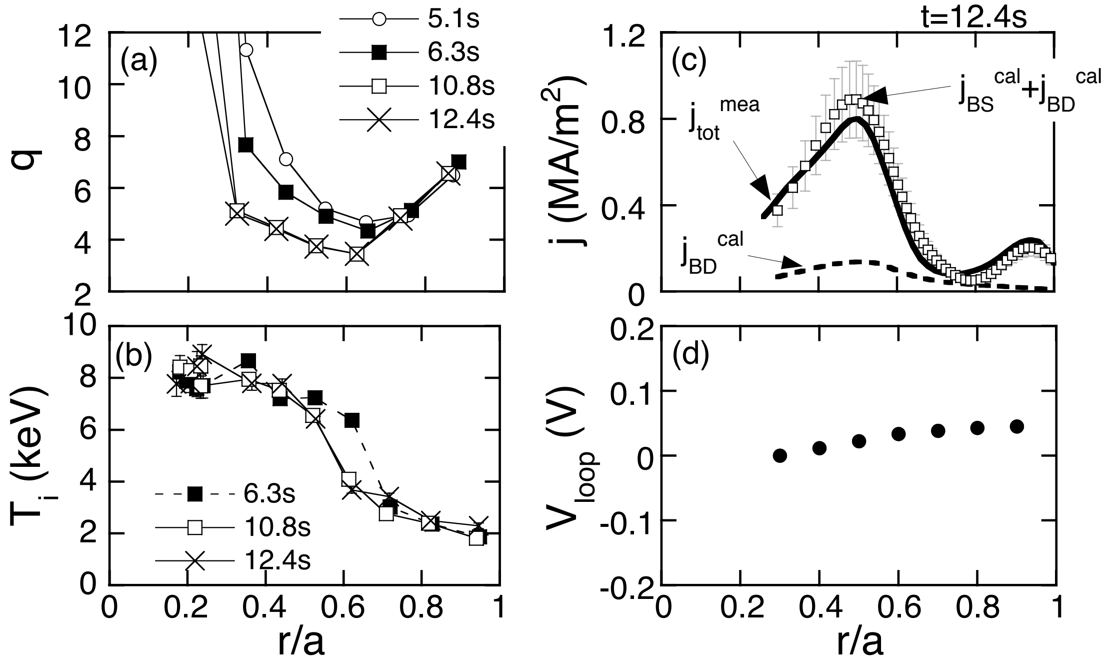

FIG. 6. Time evolution of (a) q profile and (b) ion temperature profile. (c) Profiles of measured total current density (j_{tot}^{mea}), calculated beam driven current density (j_{BD}^{cal}), and sum of calculated bootstrap current density (j_{BS}^{cal}) and beam driven current density at t=12.4 s. (d) Profile of time-averaged loop voltage (t=10.8-12.4 s).

non-inductive current drive condition is expected in E43046. Figure 7 shows the progress in the quasi-steady f_{BS} on JT-60U. It is obvious that the operational region of the large f_{BS} plasmas has significantly extended, which is much higher than the level of ITER steady-state operation and comparable to that of SSTR.

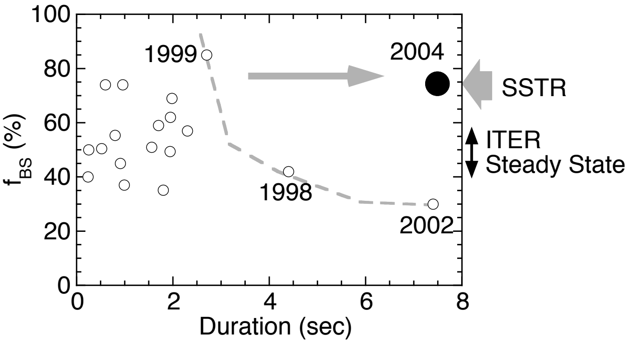

FIG. 7. Progress of sustainment of quasi-steady large f_{BS}, where sustained f_{BS} is plotted against sustaining period. Open circles indicate the results obtained before the last IAEA conference, while closed circles represent the result after the conference.

4. Summary

Recent progress in stationary discharges with a large bootstrap current fraction in JT-60U towards steady-state tokamak operation for ITER and SSTR are reported. The key factors for steady-state operations are long sustainement of high confinement and high β_N with large bootstrap current fraction under the full non-inductive current drive condition. Towards this, significant progresses were made in weak shear and reversed shear plasmas regime.

In weak shear plasma regime, high-β_p ELMy H-mode discharge has been optimized under nearly full non-inductive current drive by large bootstrap current fraction (f_{BS}~50%) and beam driven current fraction (f_{BD}>40%), which was sustained for ~2.3s. The profiles of pressure and current seem to become stationary. The high confinement enhancement factor H_{89}~2.3 (HH_{98y2}~1.0) was also sustained under the condition of T_e~T_i. During this high performance phase, no 3/2 mode was observed thanks to q_{min}~1.5.

In reversed shear plasma regime, a large bootstrap current fraction (f_{BS}~75%) has been sustained for 7.4 s under nearly full non-inductive current drive condition. The high confinement enhancement factor H_{89}~3.0 (HH_{98y2}~1.7) was also sustained. The profiles of current and pressure gradually changed in time and approached the stationary condition. One of the key points of operation is ITB control. For the long sustainment of the reversed shear ELMy H-mode plasmas, the discharges sometimes terminated by a disruption before reaching the stationary condition when the value of q_{min} passed through integer values. The disruption was successfully avoided by the control of ITB strength through the toroidal rotation control. The large bootstrap current and the off-axis beam driven current sustained this reversed q-profile. This duration was limited only by the duration of the neutral beam injection. As for the sustainment of f_{BS}, the operational region of the large f_{BS} plasmas has significantly extended, which is much higher than the level of ITER steady-state operation and comparable to that of SSTR.

Acknowledgements

The authors would like to thank the members of JAERI who have contributed to the JT-60 project.

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